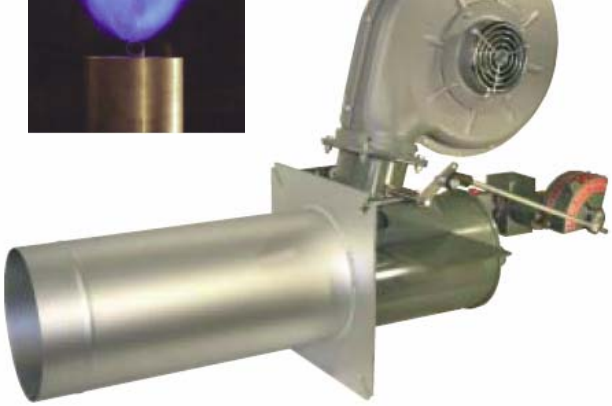
Ultra Low NO_x Burners for Industrial Processes (CPS# 1463)

Goal: Develop and commercialize ultra-low NO_x burners with exceptionally low cost/performance ratios and enhanced system efficiency for direct and in-direct industrial heating applications

Challenge: Lean premixed combustion is an excellent passive control method for NO_x reduction but needs robust, economical, scalable, and easily adaptable designs to meet diverse system requirements

Benefits: Robust, simple, and reliable pollution reduction technology for most industrial processes. Energy savings by lowering parasitic energy losses and enhance efficiency through “smart” system integration

FY05 Activities: Establish technical foundation for lean/lean fuel staging strategy to increase system efficiency



Participants: Lawrence Berkeley National Laboratory, Maxon Corp, CMC Engineering, Coen Co., MidCo Int’l, PowerFlame, John Zink Co

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Barrier-Pathway Approach

Barriers

- Emissions/efficiency tradeoffs – complex burners consume more power
- Reduced performance – limited turndown, flame instability, drop off at partial load
- Higher costs – manufacturing, capital, & operating

Pathways

- Adapt lean premixed low-swirl burners for process heat and boilers
- Develop engineering rules for scaling and system integration
- Energy savings through performance enhancement methods and "smart" system optimization

Critical Metrics

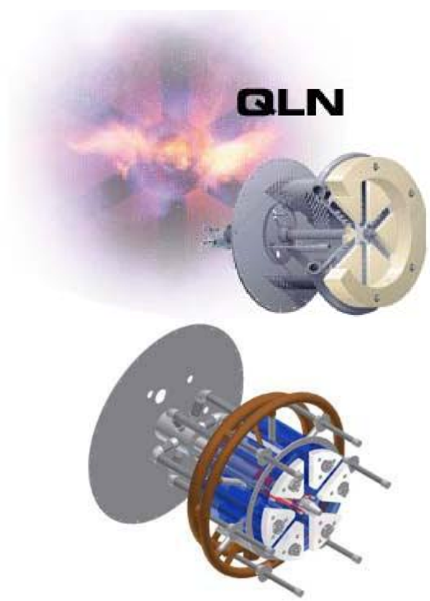
- Industrial < 9 ppm NO_x burners with performance range and costs matching those of conventional burners
- Technical foundation for < 5 ppm NO_x systems

Benefits (est.)	2020
Energy Savings	Good potential
Cost Savings	High
NO_x Reduction	Very High

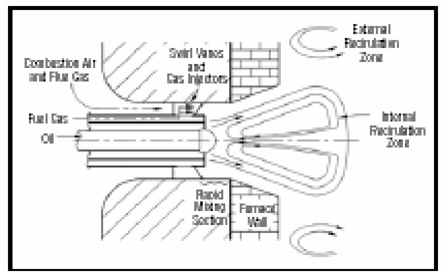
Technical Background - Conventional Nozzle Mixed Burners vs. Advanced Premixed Burners

- ***Nozzle mixed burners (diffusion flames)***
  - High flame temperature and high NO_x due to burning at close to stoichiometric fuel/air conditions
  - High turndown (> 10:1), robust, reliable, and fuel flexible
  - Not easily amenable to NO_x control
- ***Premixed burners***
  - Low flame temperatures of lean flames lower NO_x
  - Flame holders dictate performance (< 5:1 turndown) & limit fuel flexibility
  - Flame generated flow dynamics are safety and reliability concerns

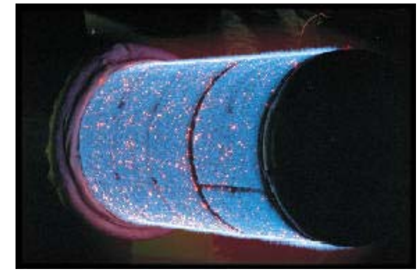
Technical Background -
Examples of Current Low-NO_x Approaches



- Coen Quantum Low NO_x Burners have highly staged rich/lean zones



- Todd Combustion Rapid-Mix Burners use hybrid diffusion and premixed flames



- Alzeta burners use surface stabilized premixed combustion

Challenges for ultra-low NO_x operation

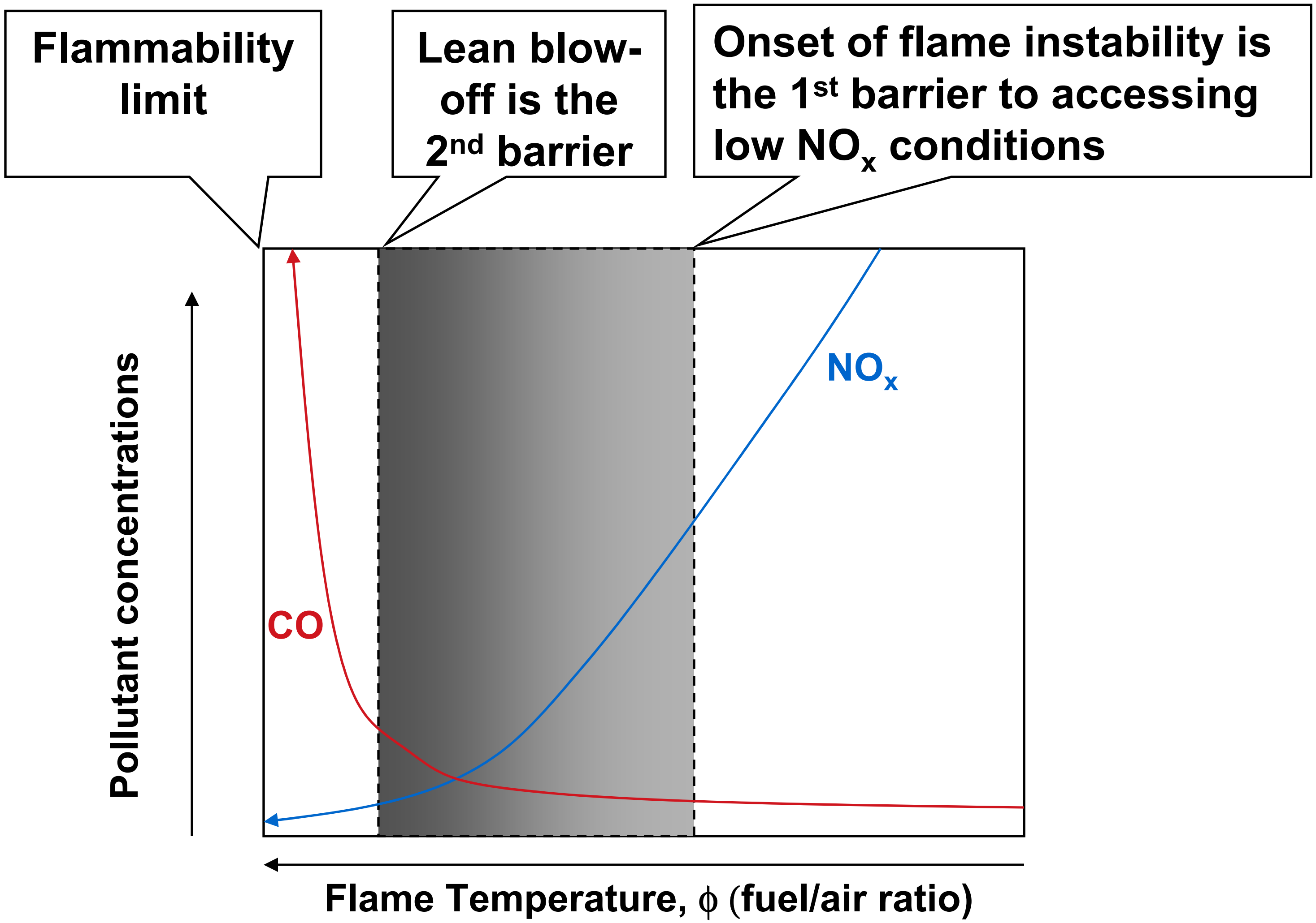
Scaling, staging, turndown, flame stability, controls & cost
Burner/chamber coupling and fine adjustments for system integration
Economically acceptable designs for smaller industrial systems

Our Approach –
Premixed Flames Stabilized by Low Swirl

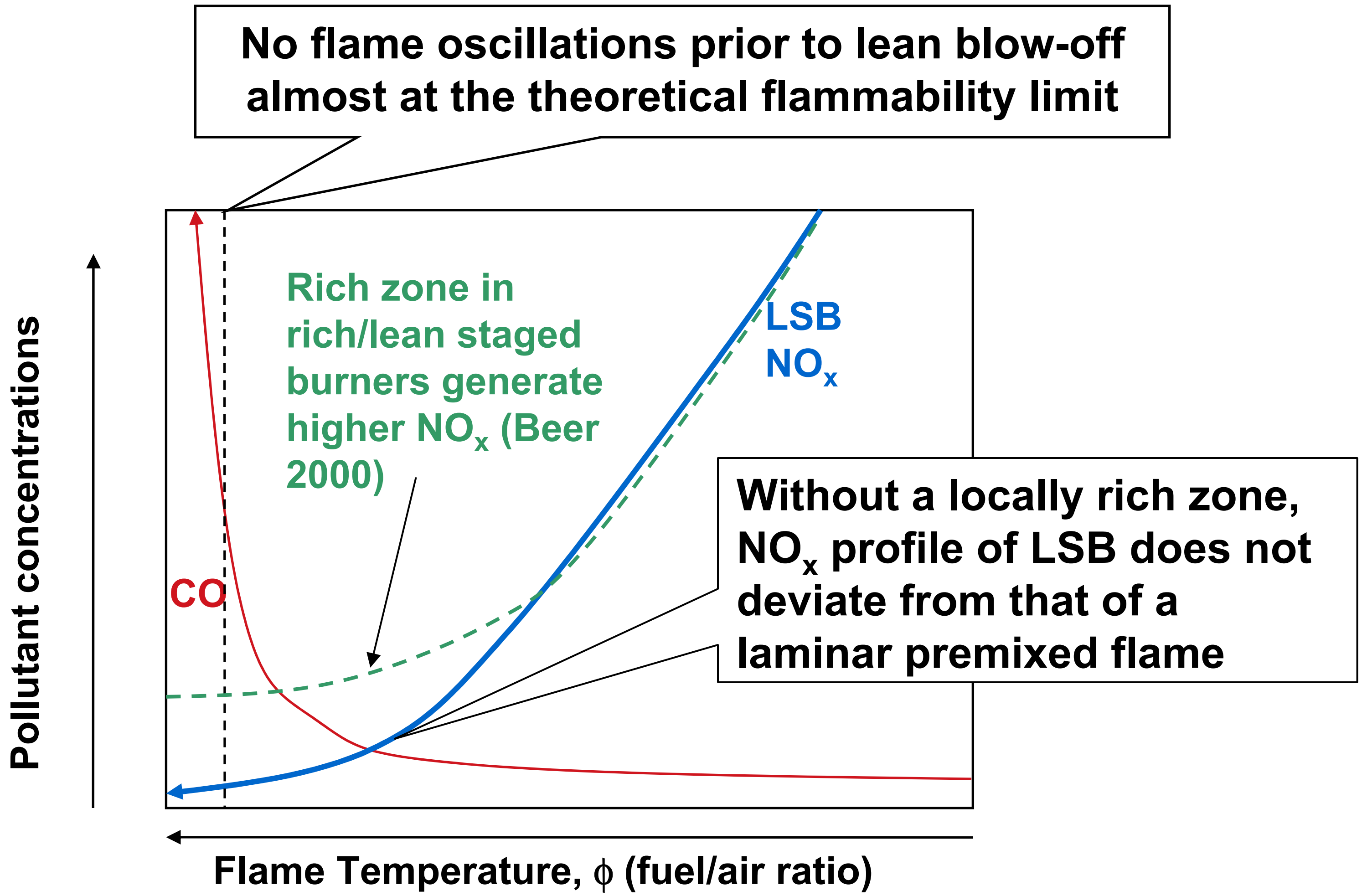
- ***Novel method discovered in 1991 at LBNL***
  - Laboratory burner for DOE-BES basic research
  - Flame stabilization principle understood
- ***Scientific Interest***
  - Challenging modeling problem
  - Excellent for studying flame turbulence interactions
- ***Technological Interest***
  - Robust rich to ultra-lean flames
  - Simple design
  - Patent awarded 1998

Original laboratory LSB with air-jet swirler at 30 kBtu/hr

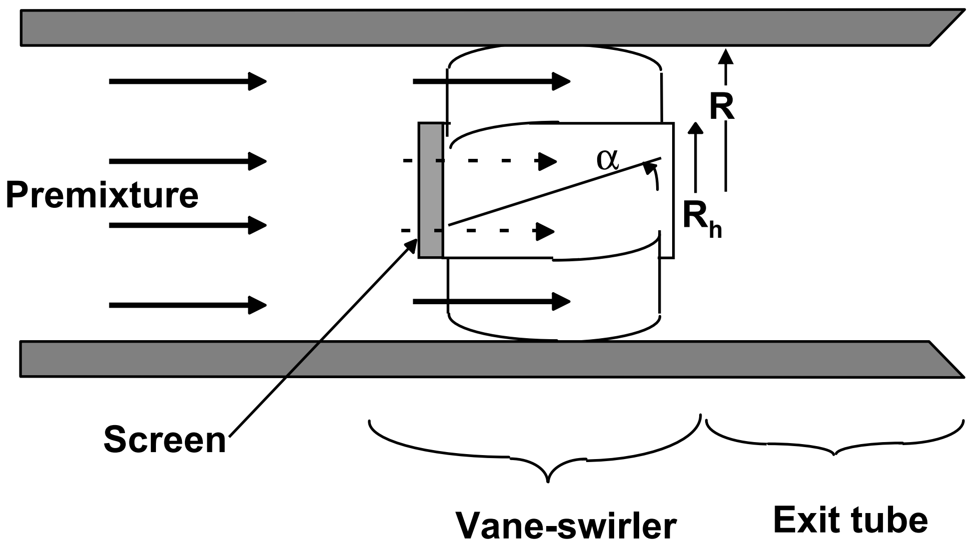
LSB Circumvents Flame Instabilities & High Lean Blow-off Problems Associated with Conventional Flame Holding Methods

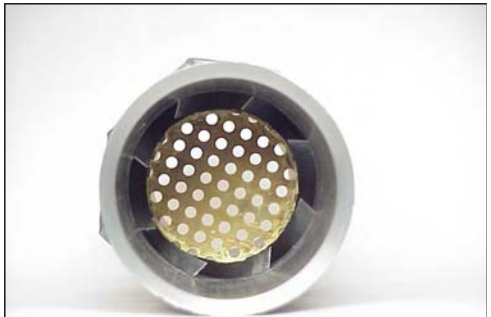


LSBs Access Low NO_x Conditions by Exploiting Aerodynamics of Lean Premixed Flames Instead of Trying to Overcome Them



Vane-Swirler Developed for Commercial and Industrial Applications





Top view of patented vane-swirler

- ***Simple design fundamentally different than conventional vane-swirlers***
  - Open center channel allows a portion of flow to bypass swirl vanes
  - Angled guide vanes induce swirling motion in annulus
  - Screen balances flows between swirl and center channel
- ***Patent awarded in 1999***

Swirler for LSB is Simple and Low-Cost

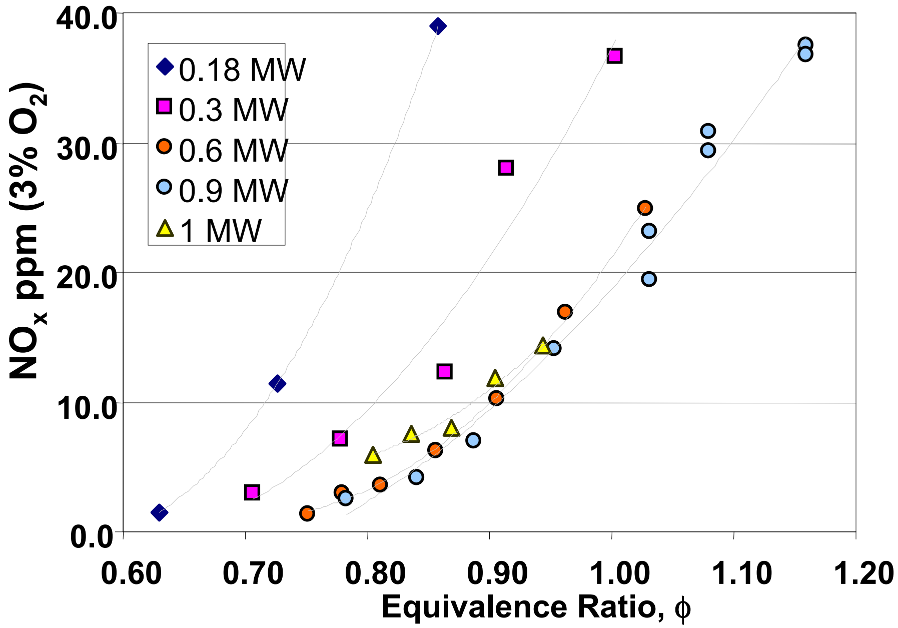
This burner is made of PVC and plastic to showcase the uniqueness of LSB

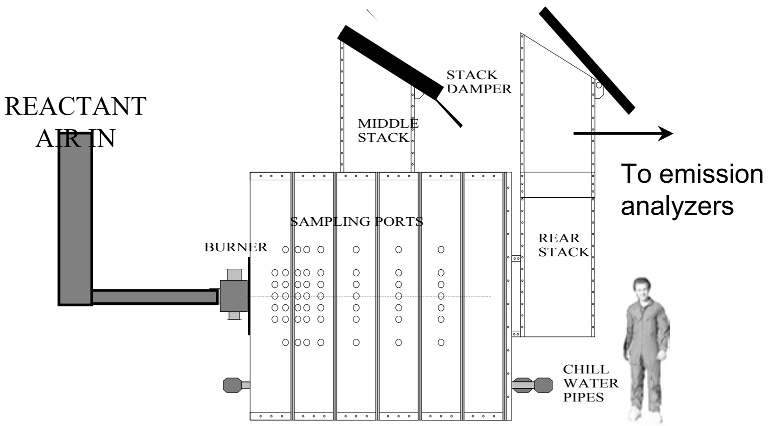
- Precision machining not required
- Lifted flame does not transfer heat to burner throat
- Estimated fabrication cost of < $10/unit for pool heaters of 300 KBtu/hr much lower than $100/unit cost of metal fiber burners

Scaling to Industrial Sizes

- ***Scientific approach for "smart" adaptation to a broad range of process heat and boiler applications***
  - Targeting 300 KBtu/hr to 30 MMBtu/hr burners
- ***Establish scaling rules***
  - Obtain scientific background for low-swirl flows
  - Apply theory on turbulent flame speed to predict blowout/flashback
  - Evaluate trade-off/benefit between two scaling approaches
    - Higher flow velocity vs larger burner diameter
  - Optimize burner to fit chamber geometry

Obtaining Scaling Information Through Laboratory Experiments





- Comparing LSBs of different sizes (2 – 5“) in furnace and boiler simulators with and without FGR (Partnering with CMC Eng., UCI, Maxon, TIAX, Zink and Aqua-Chem)
  - LSB not vulnerable to slight changes in velocity and mixedness
  - NO_x emissions depend primarily on air/fuel ratio
  - Observed 30:1 turndown

Laser Experiments Provided Scientific Explanation for LSB's Robust Performance

- **Analyses drawn upon the theories on combustion aerodynamics and flame chemistry**
- **LSB self-similar flowfield key to its robust operation**
- **Knowledge essential for identifying, prioritizing and resolving operational issues**
  - Placement of flame ignitor
  - Protocol to maintain flame stability during load change
  - Premixing requirement
  - Conditioning of flow supplied to the burner

Found Answers to Key Scaling Questions

- **What are the critical roles of LSB components on its operation?**
  - Size of center channel: Controls back pressure
  - Exit tube length: Minimum length needed for proper operation
  - Vane angle: Flame discharge angle
  - Vane length: Improves turndown but can increase back pressure
  - Screen placement position: Upstream placement preferred
  - Screen type: Not critical
- **How high can we push the throughput?**
  - From 8 to 270 ft/sec without swirl adjustment
- **Does burner diameter change its performance?**
  - No, flame stability and operating range are size independent
- **Is there a convenient scaling rule that engineers can use?**
  - **YES!**

Engineering Rule 1st Step – New Derivations of Swirl Number to Quantify Swirl Rates

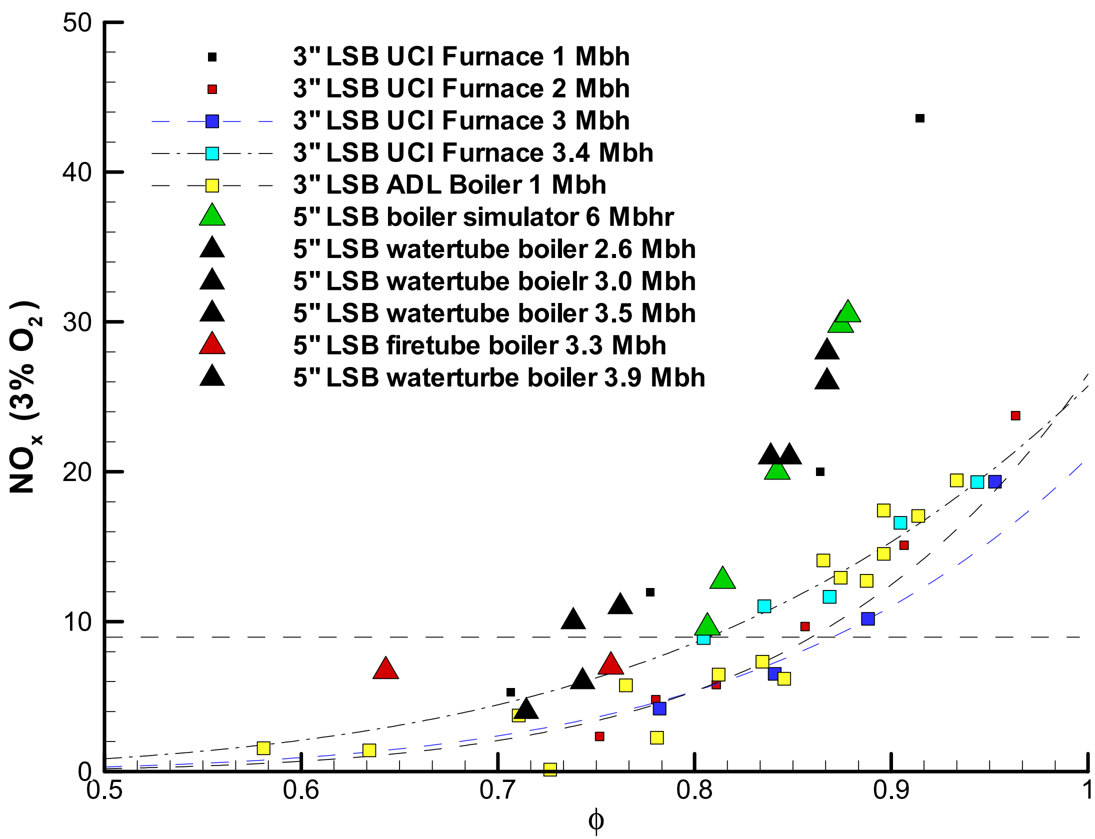
$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2}$$

- New expression uses easily measurable parameters
  - **Ratio of center channel radius to burner radius, $R = R_c/R_b$**
  - **Straight or curved vane with angles, α**
  - **Ratio of mass flow rates through center channel and swirl annulus, *m***
    - **Standard pressure drop procedure to obtained *m* from different screens**

LSB Scaling Rules

- **Keep swirl recess at 1 to 1.5 diameter**
- **Apply 0.4 < S < 0.55 criterion**
  - Center-channel/burner ratio 0.5 < R < 0.6
    - Larger R increase drag thus blower power
  - Vane angle between 37^0 to 45^0
    - Vane can be curved or straight
    - Overlapping vanes increase turndown
  - Optimize burner by using different screens to change S
    - Screen geometry is not critical
    - Larger openings reduce clogging
    - Other options available to change ***m***
- **Constant velocity scaling for power output**
  - Output power scaled by the square of the burner diameter
  - Minimum operating conditions at bulk flow of 10 ft/s
- **Optimum flame closure at 3 to 4 R_b**

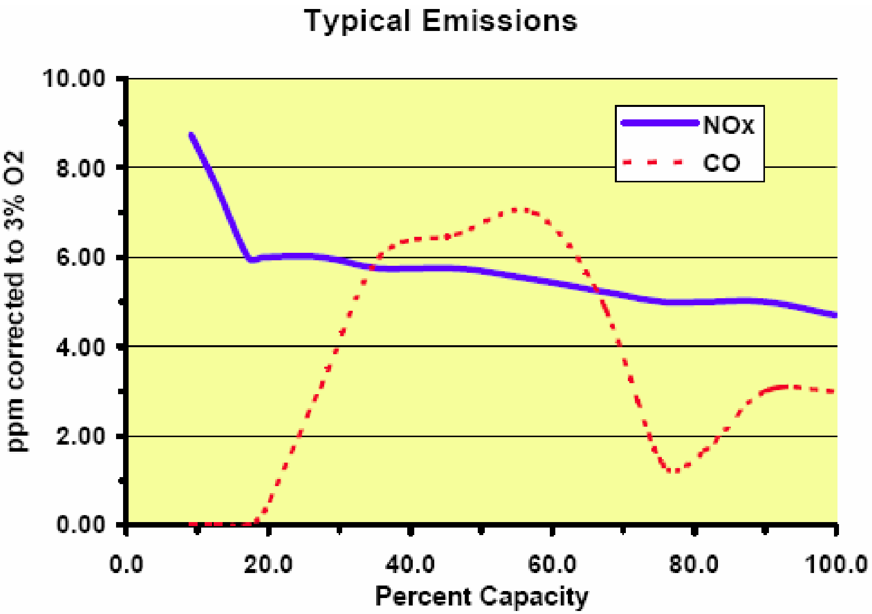
Applied Engineering Rules to Scale LSB up to 20" and 25 MMBtu/hr



- NO_x correlates primarily with air/fuel ratio
  - Chamber geometry has some effect due to internal flow pattern and residence time
  - Cross < 9 ppm (3% O_2) threshold at 3% to 5.5% O_2
- LSB flame is quiet and remains stable even at high excess air and FGR

Commercialization for Process Heat

- Maxon Corporation licensed LSB in 2002
- Target ultra-low NO_x market (< 9 ppm at 3% O_2 guaranteed) for industrial heating, baking and drying
- First products of 1 – 6 MMBtu/hr, 10:1 turndown available since Sept. 2003
- 33 units shipped and SCAQMD BACT certification pending
- Demonstrated improvement in product quality for paint curing and food processing
- Products up to 25 MMBtu/hr being developed targeting 20:1 turndown



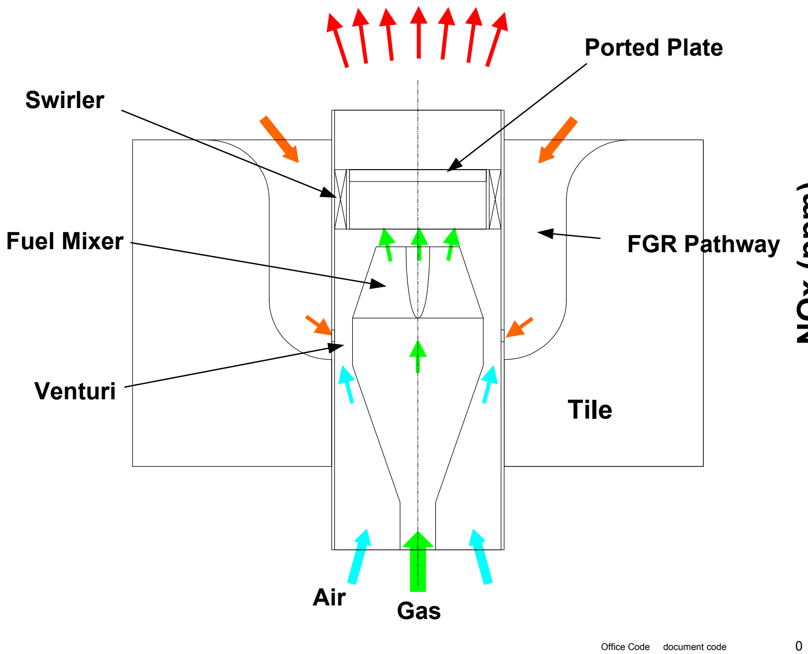
Maxon Identified Significant Economic and Technical Advantages of LSB

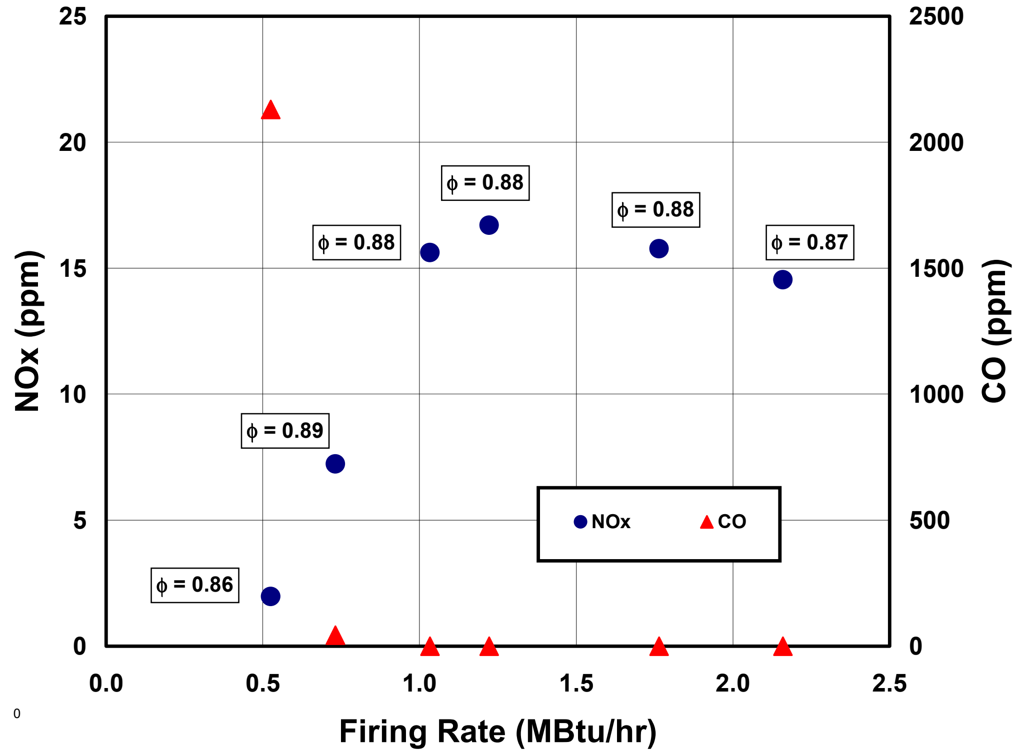
- Design scales by governing equations
  - A radical departure from experimentation approach
- Size compatible to existing equipment
- Can be fabricated with no initial re-tooling or new patterns - fewer parts made of common materials
- Use existing control for conventional high NO_x burners
- Flame is not in contact with burner tip
  - No thermal stresses to cause metal fatigue
- Lower operational cost, and greater ease of operation, thanks to simpler combustion process

LSB Adaptation to Indirect Heat & Implementation of Enhancement Schemes

- **Reduce operating back pressure of LSB (accomplished)**
  - > 50% reduction with no change in performance
  - Obtained drag coefficients for sizing fan power
- **Flue gas recirculation (demonstrated & in progress)**
  - TIAX developed and tested internal FGR/premixer
  - Tests in boilers with external FGR (Zink, Aqua-Chem, & Coen)
- **Partial reforming to reach < 2 ppm NO_x (demonstrated)**
  - Traces of H_2 enhance flame stability and lower CO
    - Steam reformer (CMC Engineering & Sud-Chemi)
    - Instant on plasmatron reformer (MIT)
- **Lean/lean Fuel Staged LSB (in progress)**
  - Consumes excess air from first stage lean flame (Maxon)
- **Highly preheated combustion (demonstrated from DOE-DER gas turbine project)**
  - Increase efficiency through heat recovery

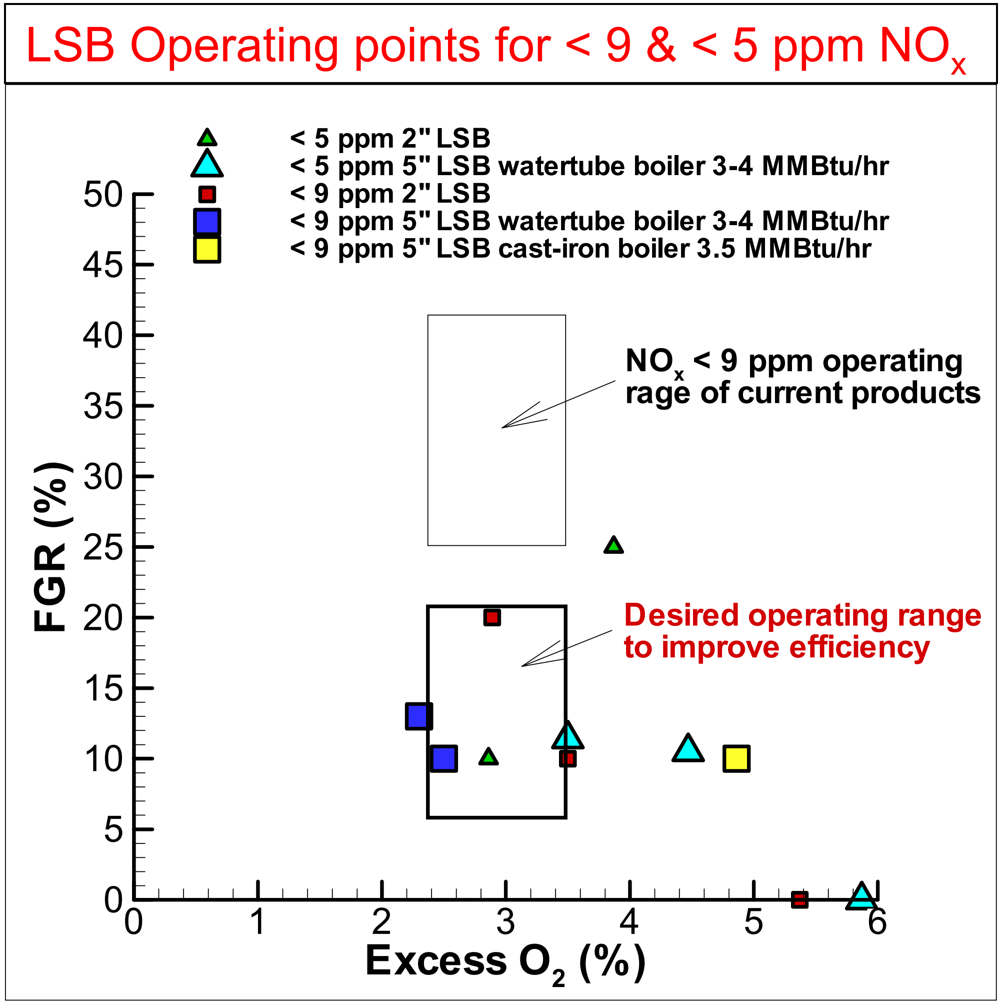
TIAX Developed and Tested Venturi Premixer and FGR Entrainer for LSB

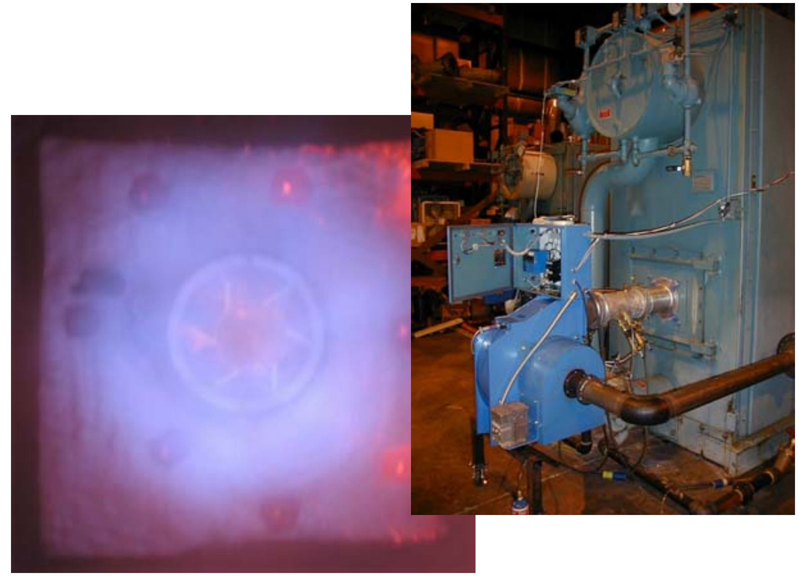




- Computation fluid dynamics (CFD) to optimize design for a *R* = 0.8 LSB at 7.5"
- Higher than expected NO_x attributed to in-chamber circulation

LSB Tested in Commercial Watertube & Firetube Boilers with External FGR

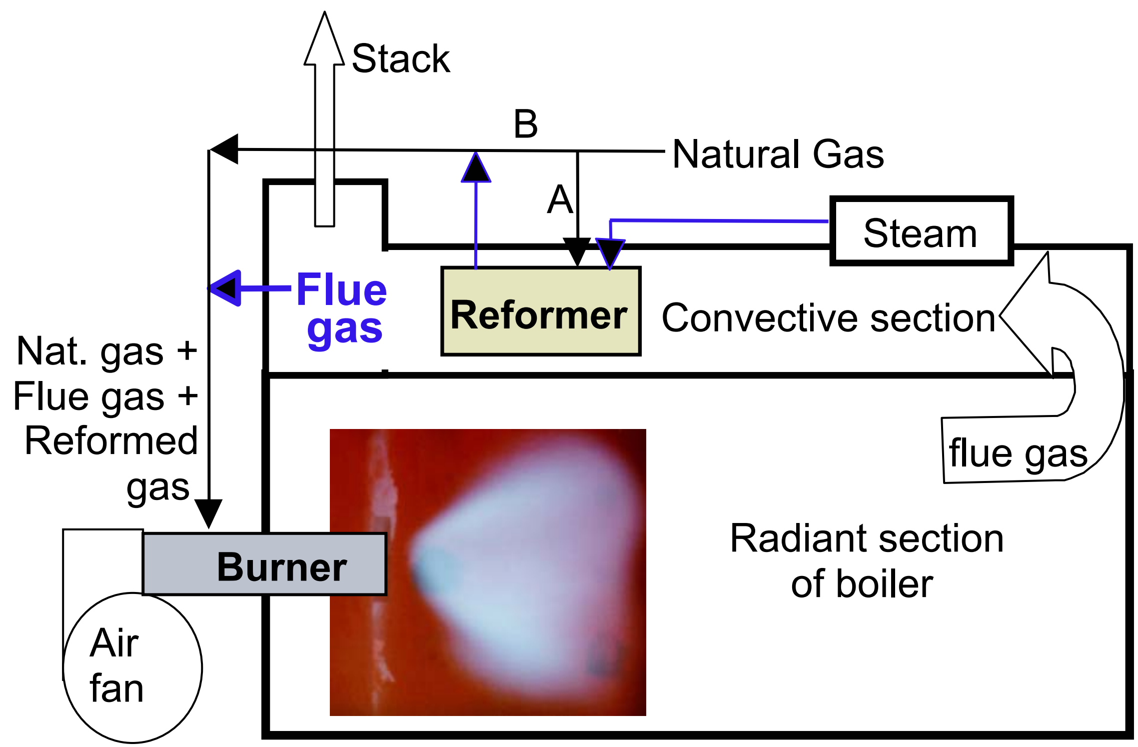




- Use blower and controls for the commercial boiler
- Demonstrated low NO$_x$ at partial load
- LSB shows good promise for improving system efficiency

2 ppm NO_x Concept -- FGR + LSB + Partially Reformed Natural Gas (PRNG)

- **Exploit combustion of hydrogen enriched natural gas**
  - Enhance flame stability & CO burnout
  - Use LSB to capture these benefits
  - Partial reformer to produce optimum H_2:CH_4 ratio in fuel
- **Developed prototype partial reformer**
- **Concept verified in 50 KBtu/hr spa heater**
  - $0 < FGR < 0.3$
    $0 < PRNG < 0.05$
    $0.7 < \phi < 0.9$



Laboratory Demonstration of LSB/FGR/PRNG Concept for Boilers

- Developed and evaluated partial reformer prototype
  - Capability to follow load
  - 2 to 10 liter/MW are reasonable in a typical boiler
- Concept demonstrated in water heater simulator
  - PRNG (**5%**) helps maintain flame stability at high FGR
  - PRNG has no effect on NO_x but is effective in reducing CO
  - Steam (≈5%) has no effect on LSB performance
  - Broadened NO_x-CO valley to access 2 - 5 ppm NO_x
- Energy to operate LSB/FGR/PRNG scheme consistent with current low emissions systems
  - Estimated 0.7% efficiency tradeoff for reforming to 20% H_2

Progress Summary

- **Developed and applied scientific based engineering rules for scaling and adaptation of LSB to process heat and boilers**
  - Understanding of the roles of combustion chemistry and combustion fluid mechanics enables a “more science less art” approach
- **Commercialized < 9 ppm NO_x burners for direct process heat (0.3 - 6 MMBtu/hr) and assisting Maxon in developing > 30 MMBtu/hr burners**
  - Met emission targets, exceeded cost/performance expectation
- **Collaborating with four companies to develop < 9 ppm NO_x LSB for boilers of up to 10 MMBtu/hr**
  - Requires 50% less FGR, demonstrated ease of adaptation and load following
- **Exploring next generation < 9 ppm NO_x LSB using lean/lean staging scheme to further improve efficiency**
  - LSB provides unique lean core for staging
- **Demonstrated LSB/FGR/PRNG concept for 2 ppm NO_x boiler systems**
  - Seeking new partners on scaled up LSB with internal FGR + PRNG

Outlook

- **Develop scaling rules for adapting LSB to different boiler shapes**
  – Guidelines to adjust LSB design for different chamber geometries
  – Prevent undesirable in-chamber flow pattern
- **Field demonstration of LSB for small boilers and H_2O heaters**
  – Zink, Coen, PowerFlame, & MidCo Int'l
- **Seek partnership to develop LSB for large boilers (> 50 Mbh)**
- **Develop lean/lean Fuel Staged LSB (FSLSB) scheme for in-direct process heat**
- **Continue development of the LSB/IFGR/PRNG burner system**
  – Highly preheated air and FGR for FSLSB
- **New system designs to capture full benefit of LSB**
  – Optimize heat transfer from a more compact flame
  – Better recovery or utilization of waste heat

Market Potential & Commercialization Plans

Direct fire process heat applications of 0.3 - 50 MMBtu/hr

Commercialization Plan: already commercialized for 0.3 – 6 MMBtu/hr, larger capacity products being developed

Indirect fire process heat application of 5 – 50 MMBtu/hr

Market Potential: Excluding boilers and petrochemical furnaces, total markets for indirect fired burners are substantial in energy usage (0.8 to 1.0 Quad) and are larger than those of direct fire burners

Plan and progress: laboratory study of fuel staged LSB to develop a prototype burner that will achieve 9 – 15 ppm NOx with < 10% O2

Steam and Water Boiler 0.3 – 10 MMBtu/hr

Market Potential: Scale down of low-NO_x and ultra-low NO_x burners developed for larger boilers to these smaller sizes may not be economically feasible

Plan and progress: Planned demonstration in boilers up to 10 MMBtu/hr

Products: Test results, scaling rules and engineering guidelines

Method of dissemination: participate in laboratory tests and field trials with burner OEMs.

Large boilers up to 100 MMBtu/hr

Market Potential: LSB for indirect fire process heat has already been demonstrated at 25 MMBtu/hr and this design should also be applicable to large utility boilers
Plan and progress: Seeking research partners
Products: Test results, scaling rules and engineering guidelines
Method of dissemination: participate in laboratory tests and field trials with burner OEMs

Petroleum Refinery

Market Potential: already demonstrated to operate on mixtures of H_2 and hydrocarbons
Plan and progress: Seeking research partners to continue development
Products: Test results, scaling rules and engineering guidelines
Method of dissemination: participate in laboratory tests and field trials with burner OEMs